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Comparison of Single-Wavelength and Multi-Wavelength Transponders in a Physical-layer-aware Network Planning Study

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Abstract *Based on suitable system architectures and realistic specifications, transmit OSNR penalties and spectral constraints of multi-wavelength transponders are identified and analyzed in a network study. We report up to 70% less required lasers at the expense of a slight increase in number of lightpaths.*

Introduction

Optical communication networks have enabled bandwidth-hungry applications for years, and there is no end in sight to the ever-increasing traffic demand. To keep up with these demands in a cost- and power-efficient manner, optical transponder technology has continuously been improved. A key approach to decrease both cost per bit and power consumption has been to scale up the symbol rate per wavelength, with recently announced coherent optical transceivers supporting up to 140 GBd[1]. However, due to the highly challenging requirements of such a large bandwidth, in particular on the electronics, it is not clear how long this scaling of symbol rate remains technically feasible and economically sensible.

A potential way forward is to deploy optical carrier multiplexing, i.e., to use several optical tributary signals on different wavelengths per transponder unit[2]. In this case, an integrated multi-wavelength source (MWS) using a single optical power supply, i.e., laser, such as an optical frequency comb can offer significant efficiency improvements over multiple single-wavelength sources (SWS), i.e., lasers, by providing several lines in one integrated component. Significant progress has been made in the MWS subsystem used to generate the lines[3]–[8]. MWSs have also been studied on a system[9]–[11] and architecture[12] level. The implications of using MWSs from a network point of view have also been analyzed, covering novel routing and spectrum allocation algorithms[13], provisioning and restoration aspects[14], different optical power supply options with respect to techno-economic aspects[15] and a network throughput study[16]. The impact of MWSs specification in a physical-layer aware network study has not been addressed.

In this paper, we analyze the impact of MWS-based transponders on a network level as to provide guidelines to their specifications and required cost savings. First, suitable architectures for MWS transmitters are described and, depending on practical parameters, realistic transmit optical signal-to-noise ratio ($OSNR_{TX}$) values are identified. Using these values along further constraints of MWSs, a network planning study is conducted with two different topologies and varying traffic requests. Comparing MWS with SWS, only a moderate increase in the number of transponders required to fulfill all traffic demands is found, which is mainly due to the lower $OSNR_{TX}$ of MWSs. This penalty is contrasted by potentially significant cost savings and efficiency improvements over SWSs. The presented study gives, to the best of our knowledge for the first time, guidelines on the required MWS specifications and required savings in order for combs to become a viable alternative to SWS transponders in future efficient optical networks.

Transmitter Architectures and OSNRs

MWSs provide multiple equally spaced optical carriers originating from a single light source. Typically, they are described by their free spectral range (FSR), number of lines, power per line (P_{line}), and optical carrier-to-noise ratio (OCNR). Due to multiple lines being generated, optical power and OCNR per line of an MWS are worse than for an SWS. To achieve a sufficiently high power that matches that of an SWS, the MWS lines must be amplified, for which two potential architectures are considered. In Fig. 1a), an architecture with a single amplifier for all lines is shown. After joint amplification in a comb amplifier (CA), the carriers are separated using a de-

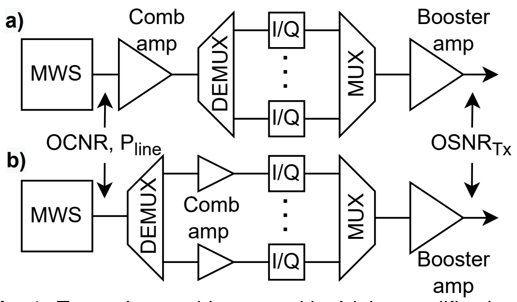

Fig. 1: Transmitter architecture with **a)** joint amplification of all comb lines and **b)** per-line amplification.

multiplexer (DEMUX) and each of them is modulated separately with an I/Q modulator. Before launching into the fiber, all carriers are multiplexed and their power is boosted to a launch power of 0 dBm by a booster amplifier (BA). The bottleneck of this architecture is the limited output power (cap) of the CA, which is typically up to 26 dBm[17]. In the second architecture, shown in Fig. 1b), this bottleneck is overcome by using a CA for each carrier, resulting into a higher number of required amplifiers. The MUX and DEMUX have a loss of 5 dB[18] each, a 5 dB modulation loss is assumed independent of the QAM format[11], and the modulator insertion and other transmitter losses add up to 23 dB[18]. The amplifiers have a 5 dB noise figure.

The additional amplifiers and the lower OCNR degrade the OSNR_{TX} of the MWS compared to an SWS. For the given parameters, the reference OSNR_{TX} is around 36 dB for a SWS with OCNR=55 dB and P_{line}=16 dBm. Using $\text{OSNR}_{\text{Tx}}^{-1} = (\text{OCNR}^{-1} + \text{OSNR}_{\text{CA}}^{-1} + \text{OSNR}_{\text{BA}}^{-1})$, we investigate the OSNR_{TX} for the two architectures of Fig. 1. The OSNR_{TX} results for the MWSs in Fig. 2 are shown over per-line power (top) and OCNR (bottom) for typical parameters[19] of OCNR=45 dB and $P_{\text{line}}=-10$ dBm, respectively. We observe that in order not to exceed a 3 dB penalty in OSNR_{TX} compared to an SWS, the power (OCNR) per MWS line must be at least -14 dBm (40 dB), which is achievable by state-of-the-art MWSs[10],[11],[19]. In the following, we analyze in a network planning study how these MWS penalties translate into additional transponders. The degrated OCNR of the local oscillator is not considered in this study.

Network Planning Study: Setup

For the conducted study, the symbol rates (SRs) and QAM formats are listed in Tab. 1. The required SNR for each configuration was obtained by taking the theoretical SNR that achieves the FEC threshold at a bit error rate of 3.5% for each QAM format as baseline and adding the implementation penalties of Tab. 1, which was based on the specifications of commercial transponders.

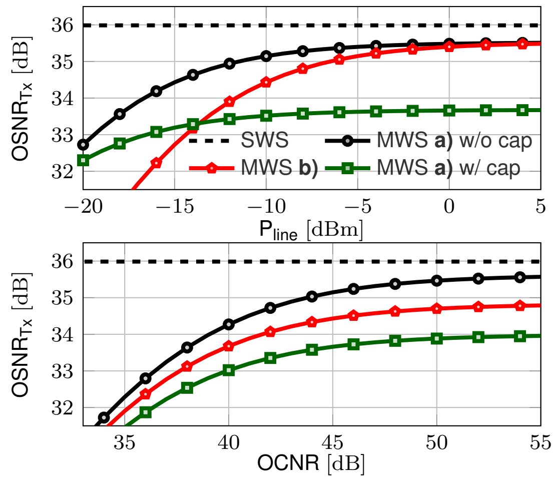

Fig. 2: OSNR_{TX} vs. power (top) and OCNR (bottom) per line for a MWS with four lines. The MWS curves relate to Fig. 1.

Tab. 1: Transponder implementation penalties in dB.

Modulation \ SR [GBd]	35	70	105	140
QPSK	1	1.5	2	2.5
16QAM	1.5	2	2.5	3
64QAM	2	2.5	3	3.5

Two network topologies were chosen for the study, representing the different characteristics of a national (Nobel-Germany) and a continental (Nobel-EU) backbone network. The links are assumed to be single bi-directional SSMF links, consisting of 80 km spans with perfect attenuation compensation at the end of each span (EDFA with 5 dB noise figure operating in the C-band). The transmit power spectral density is constant for all SRs. The considered traffic model is based on the number of data centers and internet exchange points in each ROADM location[20]. In order to vary the network traffic demands, the individual demands are scaled by the same factor in order to reach different levels of aggregate requested traffic (ART). The routing, configuration and spectrum assignment (RCSA) algorithm considers k=3 shortest-path routing and uses the first-fit algorithm for spectrum assignment. Configurations are chosen in order to minimize the number of required lightpaths (LPs). Only configurations with a required SNR threshold lower than the computed SNR are considered. The SNR takes into account OSNR_{TX}, linear noise and nonlinearities and is calculated with the closed-form GN model[21]. For flexible-FSR MWS (flex MWS), we assume that FSRs can be arbitrarily chosen and each line can be routed seperately. Hence, the only difference to SWS is the lower OSNR_{TX}. The fixed-FSR MWS (fixed MWS) with required

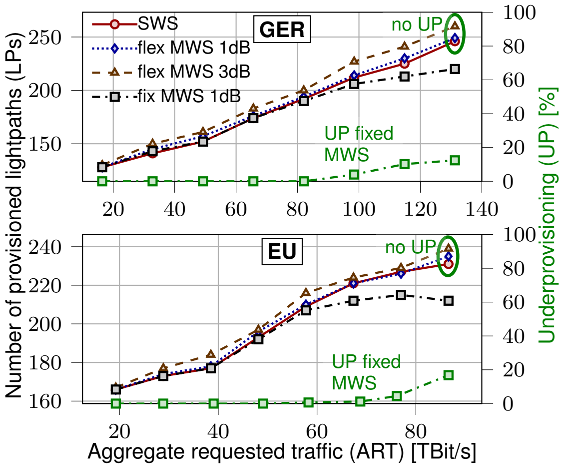

Fig. 3: Required number of LPs with respect to provisioned traffic on the Germany (upper) and EU (lower) topology. The dB numbers represent $OSNR_{TX}$ penalties of MWS over SWS.

co-propagation imposes additional restrictions on the RCSA algorithm, specifically on the spectrum assignment, as spectral slots must be allocated for all MWS lines even if not all lines are in use. All MWSs are assumed to generate four lines to provide a lower bound for MWS-based solutions.

Four different scenarios are investigated for the planning: (1) using only conventional SWS transponders, using only flex MWS transponders, assuming an $OSNR_{TX}$ penalty of either (2) 1 dB or (3) 3 dB, and finally (4) planning with fixed MWS transponders requiring co-propagation and SWS transponders. For the last scenario, a fixed FSR of 150 GHz is considered and the MWS is assumed to have an $OSNR_{TX}$ penalty of 1 dB. Also, the RCSA is modified to use SWSs whenever a demand can be met by placing a single LP. Otherwise, a fixed MWS transponder is placed and spectrum is allocated for all lines of the MWS while only the lines needed to meet the traffic demand are activated.

Network Planning Study: Results

Fig. 3 shows the number of required LPs for varying ART for both topologies and all planning scenarios, as well as underprovisioning (UP) for the fixed MWS scenario that describes the ratio of requested data rate that cannot be provisioned to ART. On the Germany topology, the number of required LPs in the flex MWS scenario with 3 dB penalty is up to 7% higher than for the SWS scenario, whereas this difference is only at most 3% for the EU network. This is due to a longer average path length of 1100 km on the EU topology compared to 420 km for Germany, which gives a smaller impact of the $OSNR_{TX}$ penalty on the overall SNR. The performance of the fixed MWS scenario is close to SWS in terms of required

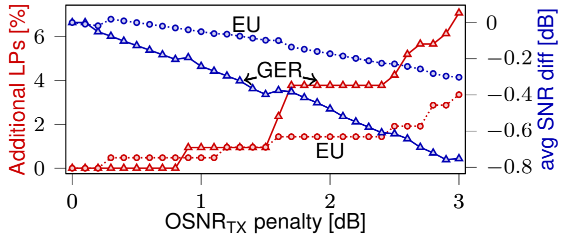

Fig. 4: Impact of flex-MWS $OSNR_{TX}$ penalty on additionally required LPs (left) and average SNR difference between SWS and MWS transponders (right).

number of LPs. This scenario, however, is less efficient in terms of the usage of spectrum, as extra slots are allocated for unused MWS lines. Therefore this scenario exhibits UP for high ART levels, as shown in Fig. 3. As ART increases further, the high spectral occupancy causes the number of deployed LPs to stay approximately constant, showing only small variations due to increases in requested traffic for individual demands and leading to increasing UP. The investigated flex MWS scenarios reduce the number of required optical power supplies by approx. 70% compared to the SWS scenario. For fixed MWS, due to co-propagation, savings up to 40% (10%) on Germany (EU) topology are achieved. Assuming 33% of the overall transponder cost is the SWS, a four-line flex MWS should cost less than 2.6 times an SWS, to be economically viable.

For fixed ART, Fig. 4 shows the impact of $OSNR_{TX}$ penalty on the required number of LPs as well as the SNR (averaged over all deployed LPs) of MWS minus SWS. We observe that using MWSs in a network study leads to minor drawbacks such as additional LPs for flex MWSs.

Conclusions

In this network planning study, we consider specifications of state-of-the-art MWSs for high-bandwidth transponder configurations. For 4-line flexible MWSs, we show savings of around 70% in the number of required lasers. In exchange, up to 7% additional transponders are required for flexible MWSs with 3 dB $OSNR_{TX}$ penalty. Fixed MWSs also offer savings in required lasers without requiring additional LPs, but can cause underprovisioning for networks with high spectral occupancy, motivating MWS-aware RCSA algorithms[14]. DSP benefits[22]–[24] offered by MWSs as well as higher MWS line number are to be treated in future work.

Acknowledgements

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